BOUNDARY-LAYER STABILITY ANALYSIS OF LaRC 8-FOOT LFC EXPERIMENTAL DATA

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ABSTRACT

An analytical study of linear-amplifying instabilities of a laminar boundary layer as found in the experimental data of the LaRC/8-Ft. laminar-flow control (LFC) experiment was completed and the results are presented. The LFC airfoil used for this experiment was a swept, supercritical design which removed suction air through spanwise slots. The amplification of small disturbances by linear processes on a swept surface such as this can be due to either Tollmien-Schlichting (TS) and/or crossflow (CF) mechanisms. This study consists of the examination of these two instabilities by both the commonly used incompressible (SALLY and MARIA) analysis and the more involved compressible (COSAL) analysis. A wide range of experimental test conditions with variations in Mach number, Reynolds number, and suction distributions were available for this study. Experimentally determined transition locations were found from thin-film techniques and were used to correlate the "n-factors" at transition for the range of test cases.

BACKGROUND/MOTIVATION

The design of laminar-flow airfoils is dependent upon the use of transition prediction techniques which accurately model the characteristics of the boundary layer. A technique which is widely used today is the e^n method that was developed separately by Smith[1] and Van Ingen[2]. This semi-empirical technique examines the tendency of a small disturbance wave within the laminar boundary layer to amplify over a given surface to the point where breakdown to turbulence occurs. The logarithmic amplification ratio, or n-factor as defined in figure 1, is a measure of the spatial growth in amplitude of a disturbance wave from the initial point of instability. Stability theory assumes that the most amplified disturbance (for a critical combination of frequency, wave-angle, and wavelength) is the driving mechanism behind transition. Based on calibrations of a linear incompressible theory with low-disturbance wind tunnel data, stability analyses have shown fairly consistently that transition corresponds to n-factors on the order of ten. However, since stability theory does not account for the influence of the free-stream disturbances, it seems fair to assume that n-factor calibrations are only valid between data sets with similar disturbance environments[3].

This research was conducted for several reasons: to examine the amplification of small disturbances by linear processes on a modern swept airfoil; to verify the use of a linear stability theory as a design tool through transonic speeds; and to compare and contrast the incompressible and compressible methods.

- Accurate transition prediction techniques are essential for laminar-flow airfoil design
- e^n method developed separately by Smith and Van Ingen
  - Semi-empirical technique
  - Relates stability theory (O-S Eq.) to transition
  - Uses amplification ratio as indicator of transition
- Solutions to O-S equation give local amplification rates

$$n \equiv \ln(A/A_0) = \int_{X_0}^{X} (\text{local amplification rate})\, dx$$

- Items to note:
  - Solutions depend on proper selection of f, ψ, and λ
  - Theory does not account for initial disturbance levels (A_0)
- Objectives of analysis
  - Validate codes used in design (SALLY & MARIA)
  - Examine effect of compressibility (COSAL)

Figure 1

BASIC CORRELATION METHOD

Figure 2 depicts the basic approach employed for this research. Measured pressure and suction distributions were used to calculate streamwise and crossflow velocity profiles along the chord[4]. A stability analysis of these profiles revealed the amount of TS and CF disturbance amplification from the initial point of instability. Comparisons of the measured transition locations with these calculations determined the correlated n-factors at transition.

Solutions to the governing stability equation, which is the celebrated Orr-Sommerfeld (OS) equation, provide the necessary information for analyzing the growth of disturbances within the boundary layer. Two of three disturbance variables, frequency (f), wavelength (λ), or wave-angle (ψ), must be specified with the third given by the solution to the OS equation. Analysis of TS disturbances was accomplished using a fixed frequency and wave-angle method. For incompressible flow it was assumed that the TS disturbances which amplify most are those moving in the direction of the free-stream ($\psi = 0$). Thus, the incompressible TS (SALLY)[5] analysis consisted of analysis of a range of frequencies with a wave-angle of zero. Since the two-dimensional disturbance assumption could not be used for compressible calculations, the compressible TS (COSAL)[6] analysis consisted of analysis of, first, a range of frequencies with a wave-angle of zero, then a range of wave angles for the most critical frequency. Suffice to say that the COSAL analysis can be quite time consuming. The CF analysis was accomplished with the MARIA[7] code which gives approximate solutions using a fixed wavelength and frequency method.

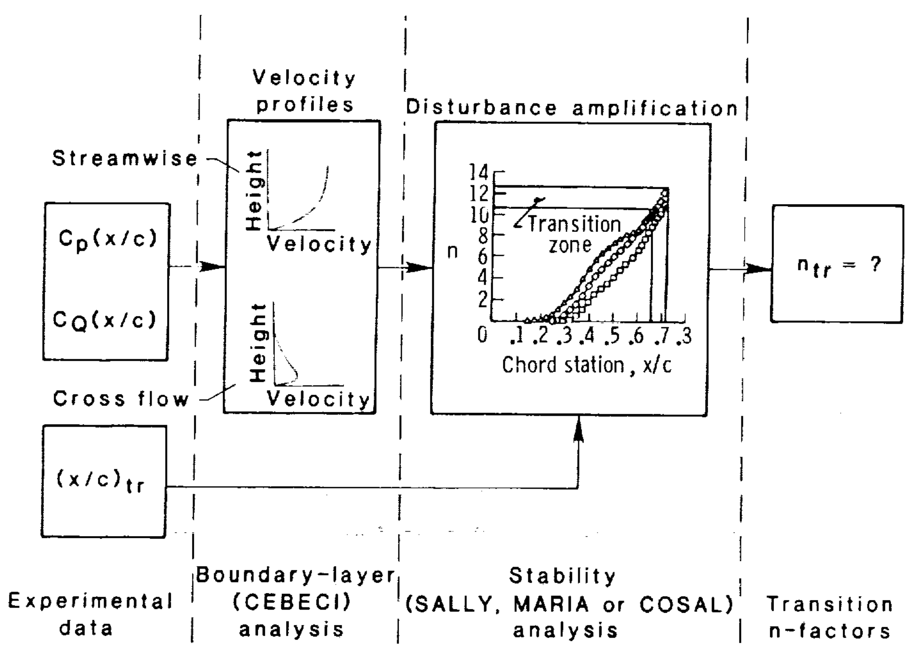

Figure 2

EXPERIMENTAL DATA

The 8-Foot LFC experiment had all the basic information necessary for a stability theory correlation - a pressure and suction distribution as well as transition measurements[8]. Because the upper surface was designed as the primary test surface, only upper surface data were analyzed. A wide range of experimental test conditions with variations in free-stream Mach number (M_∞), chord Reynolds number (R_c), and surface suction (C_q) were available for this study. As shown in figure 3, the available data encompassed both the subsonic and transonic regimes.

For the subsonic cases, the pressure distributions all had a strong leading-edge peak as is shown in figure 3 by a representative case at M_∞ = 7. The suction distributions available for these cases were all of the type designed for the airfoil with suction over the full chord. Only the overall suction levels were changed between cases without any attempt to optimize the distributions. At moderate to high overall suction levels, full-chord laminar flow was achieved for the entire subsonic range of M_∞ and R_c.

The transonic cases available were all at the design Mach number (M_∞ = .82). As is shown in figure 3, the pressure distributions for these cases closely followed the design distribution except for the slight waviness and slightly higher velocities towards the nose. The waviness in the pressure distributions was thought to be due in part to the model deflecting under loads. A sonic bubble encompassed most of the upper surface and culminated in a weak shock at the higher Reynolds numbers ($R_c \geq$ 12 million). Full-chord laminar flow was achieved until the shock appeared and then transition occurred ahead of the shock. Because of this, analysis was done on the "hybrid"-type suction distributions in which suction was systematically shut off at the trailing edge, moving towards the leading edge.

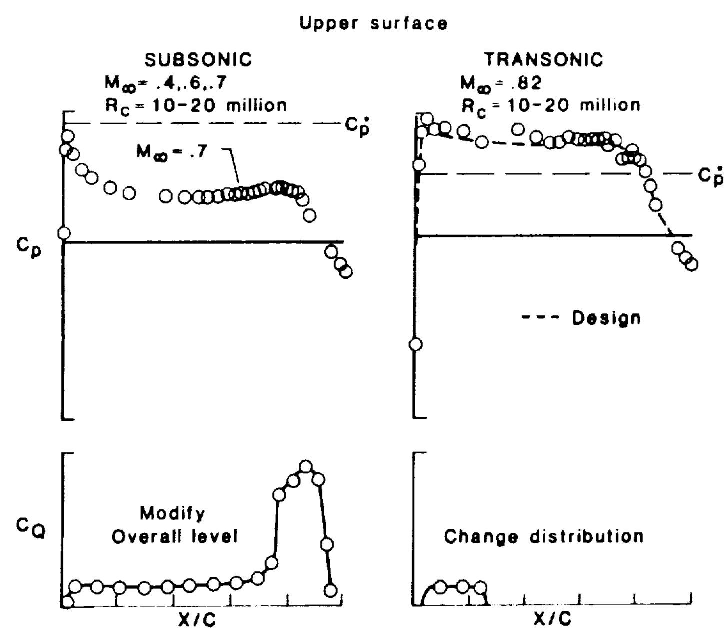

Figure 3

SAMPLE SUBSONIC CALCULATIONS

Figure 4 shows the results of an incompressible TS analysis of a sample subsonic case (M_∞ = .6 and R_c = 10 million). For the pressure and suction distributions shown in the figure, n-factors were calculated for a range of frequencies with a wave-angle of zero. The combination of the strong adverse pressure gradient near the leading edge and the full-chord suction distribution confined the TS amplification to within the first 15% chord followed by a stable region to the trailing edge. For this case, with its relatively low overall suction level, transition was measured to be around 10-15% chord. As is shown in figure 4, the TS growths reached a logarithmic amplification ratio of n = 10 in this region, for the critical frequency of f = 10 kHz.

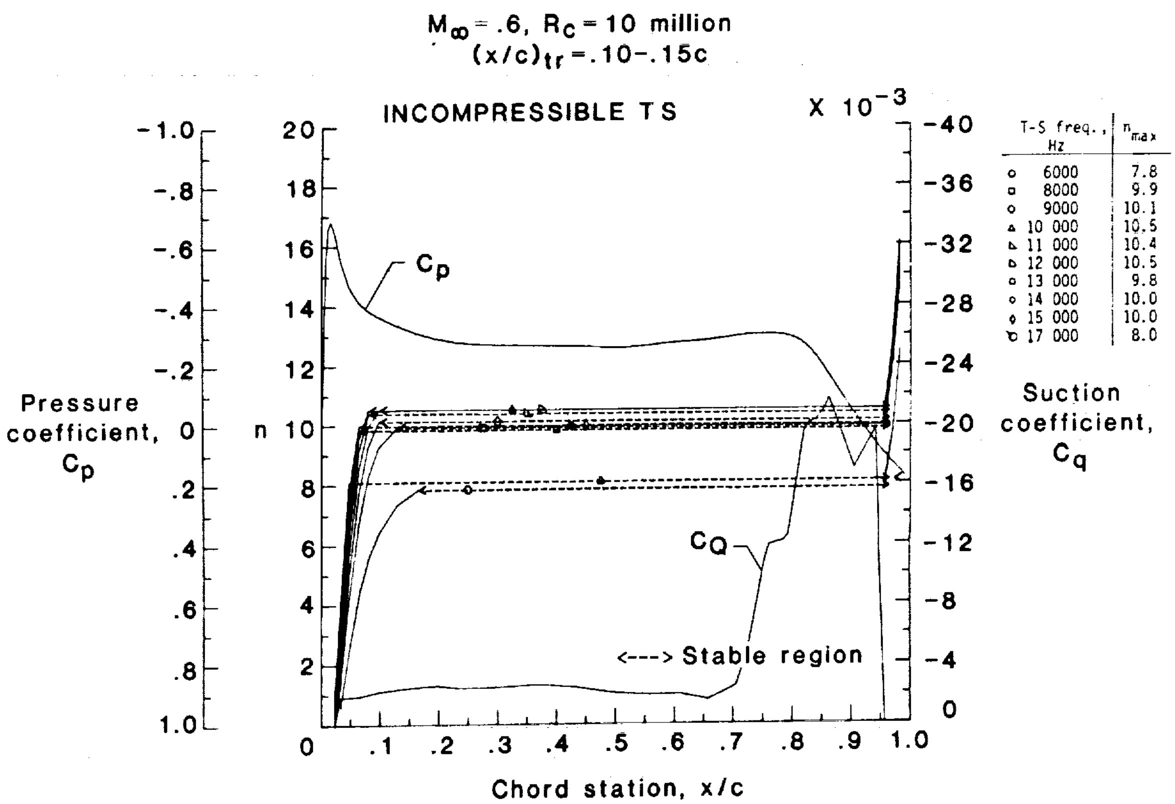

Figure 4

SAMPLE SUBSONIC CALCULATIONS

Figure 5 shows the results of an incompressible CF analysis of the sample subsonic case. The analysis indicates that CF instability is not strong enough to cause transition in this case. In fact, over the entire subsonic range of M_∞ and R_c cases available, CF logarithmic amplification ratios did not exceed n = 2.5 in the nose region where the cross-flow instability is considered to be most critical.

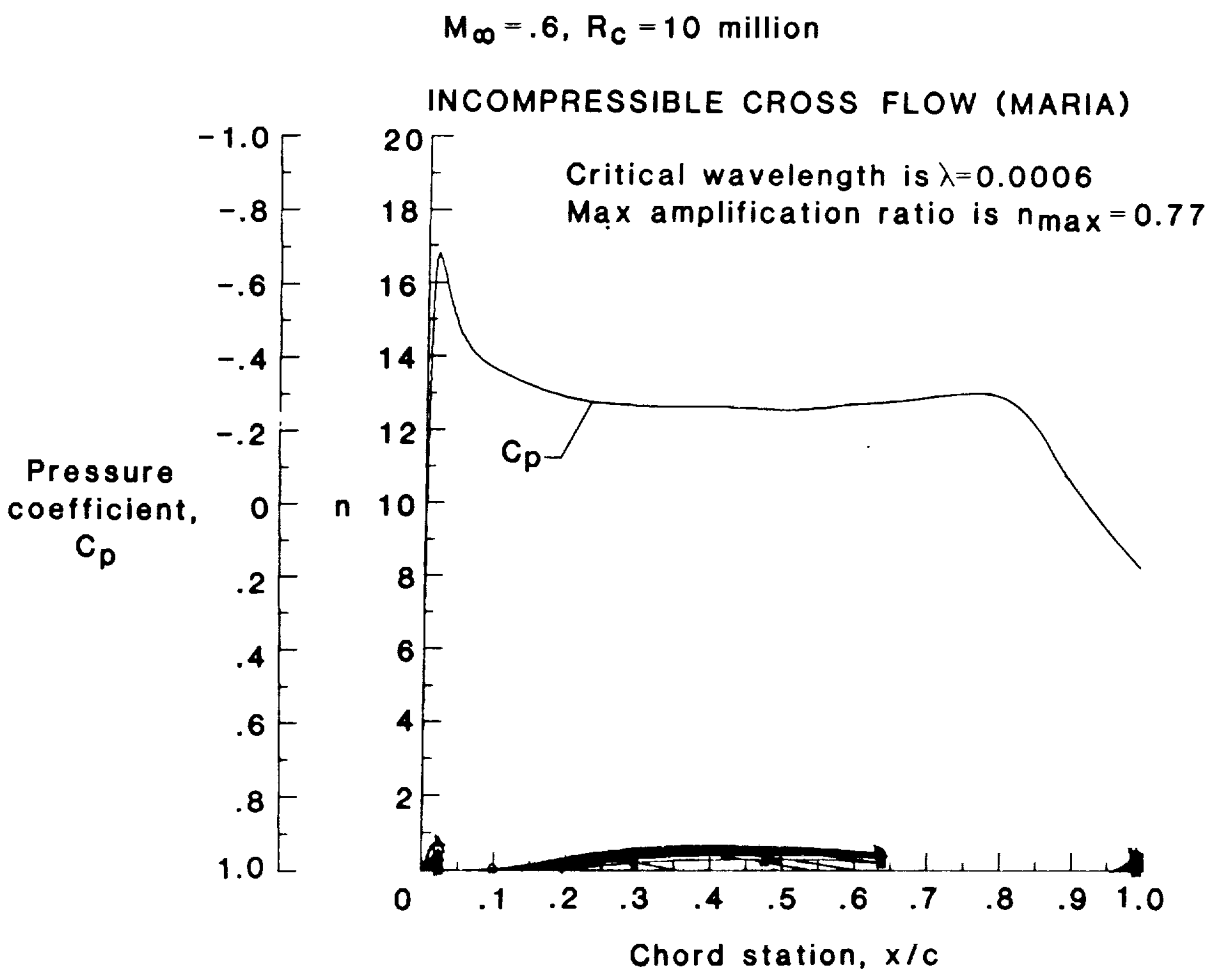

Figure 5

RESULTS OF SUBSONIC ANALYSIS

The results of the subsonic incompressible analysis are summarized in figure 6 which shows the calculated transition n-factors versus the subsonic range of Mach numbers for the Reynolds numbers of 10 and 20 million. Since CF amplification was shown to be insignificant, transition was due entirely to TS amplification. The figure shows the TS logarithmic amplification ratios that correlated with transition. The TS transition n-factors varied from n = 8.5 to 10.5 over the range of M_∞ and R_c analyzed. This variation in n-factor is attributed to the fact that the wind tunnel disturbance environment is changing with M_∞ and R_c.

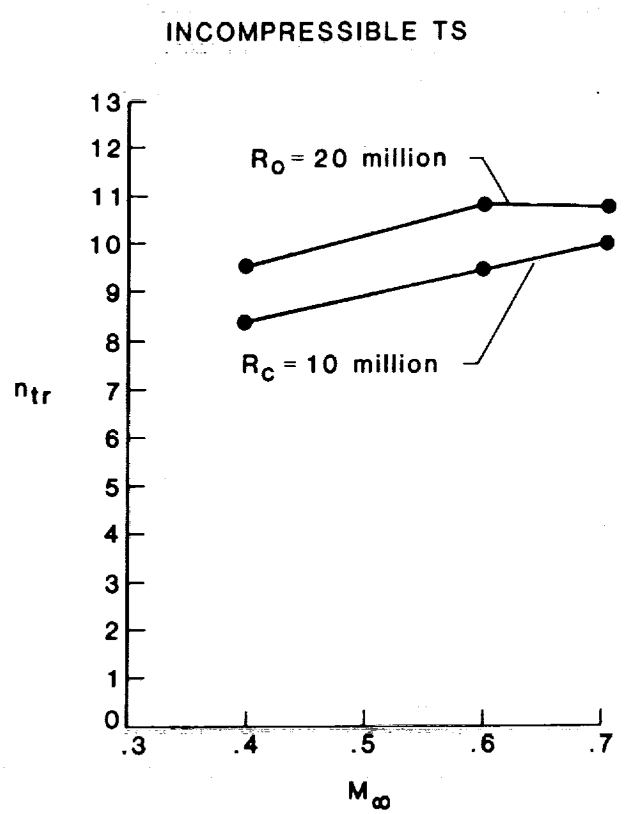

Figure 6

CONCLUSIONS OF SUBSONIC ANALYSIS

The main conclusions that were drawn from the incompressible subsonic analysis[9] are listed in figure 7. The transition process was found to be dominated by TS amplification. For these subsonic cases, transition occurred when TS logarithmic amplification ratios in the range of n = 8.5 to 10.5 was reached near the leading edge.

- CF disturbance amplification at leading edge
  - Small
  - Unaffected by suction
- Decreasing overall suction levels
  - Decreased amount of laminar flow
  - Allowed higher TS growths at leading edge
- Therefore, transition process
  - Dominated by TS disturbances
  - Occurred when n_{TS} in the range 8.5 to 10.5 was reached

Figure 7

SAMPLE TRANSONIC CALCULATIONS

Figure 8 shows the results of an incompressible TS analysis of a sample transonic case (M_{∞} = .82 and R_C = 20 million). For the pressure and suction distribution shown in the figure, n-factors were calculated for a range of frequencies with a wave-angle of zero. The combination of the wavy pressure distribution and suction being turned off after 8% chord allowed strong TS amplification to begin. For this "hybrid" case, transition was measured to occur between 20 and 28% chord. As is shown in the figure, TS disturbances grew to a logarithmic amplification ratio of n = 10 to 13 in this region, for a critical frequency of f = 9 kHz.

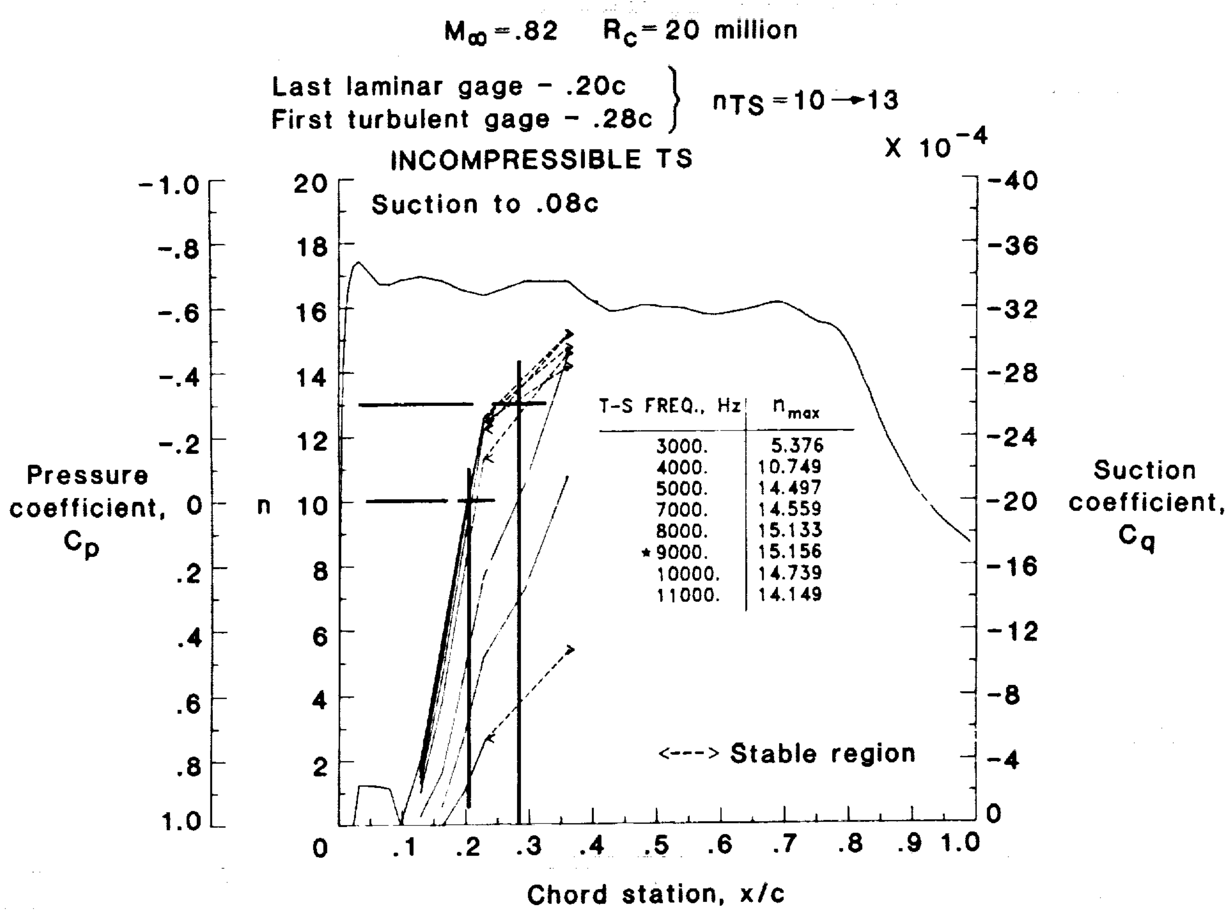

Figure 8

SAMPLE TRANSONIC CALCULATIONS

Figure 9 shows the results of an incompressible CF analysis of the sample transonic case. As is shown in the figure, CF disturbances grew quickly to a peak logarithmic amplification ratio of n = 4.5 at about 5% cord and then rapidly damped out. There was no calculated CF amplification in the region of measured transition. For this reason, it was concluded that CF disturbances did not contribute to transition. The case shown here illustrates the "worst" case calculations in terms of CF disturbances over the entire range of M_∞ and R_c.

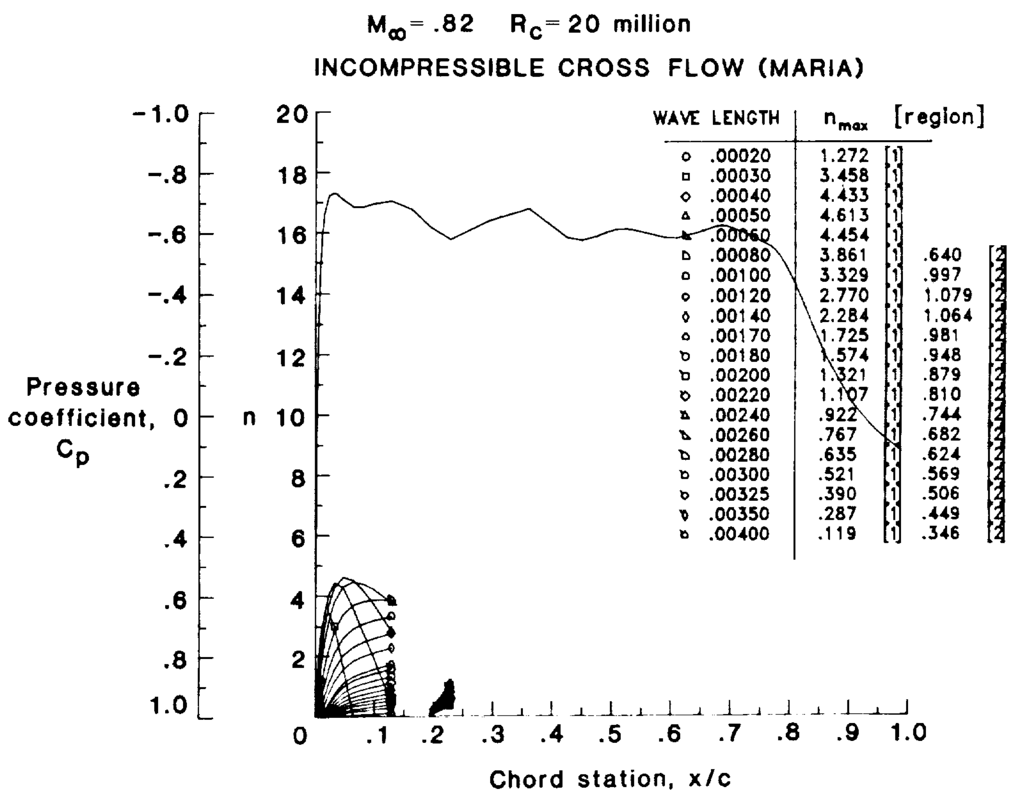

Figure 9

VARIATION OF TRANSITION FOR SIMULATED HLFC

During the experiment, an attempt was made to simulate possible "hybrid" laminar-flow control (HLFC) conditions by turning off the suction level at various chord locations. The HLFC cases consisted of measuring the extent of laminar flow as the upper surface suction was systematically shut off, at the same time maintaining lower surface suction on only the first 25% chord. This simulated HLFC approach is considered somewhat "non-idealistic" since no effort was made to seal or smooth the un-sucked regions of the airfoil. Furthermore, it is clear that the current pressure distribution (measured or theory) is not like that which would be designed for HLFC. However, these cases provide data for which transition occurs far forward of shock location thereby being ideal for a stability theory correlation at transonic speeds.

Figure 10 shows the measured variation of transition location on the LFC airfoil upper surface with extent of suction for M_∞ = .82 and two chord Reynolds numbers. For R_c = 10 million, transition occurred roughly 20% chord past the point where suction was shut off, until full-chord laminar flow was achieved. For R_c = 20 million, transition occurred roughly 10% chord past the point where suction was shut off, until the shock present on the rearward end of the model tripped transition. The data clearly indicate the extent of laminar flow that could be maintained beyond the point where suction stopped for transonic airfoils with weak-shock and shockless conditions.

SWEPT LFC AIRFOIL SLOTTED UPPER SURFACE

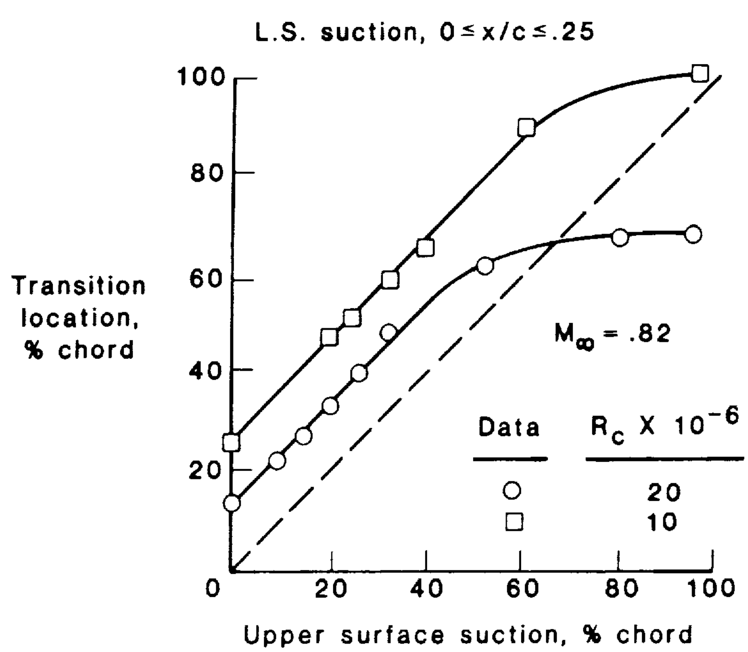

Figure 10

TRANSONIC RESULTS

Figure 11 indicates the results of the incompressible stability analysis of the HLFC data that has shockless flow on the upper surface (R_c = 10 million). The figure shows the range of TS amplification at transition versus the extent of suction applied to the airfoil. For each case in which the suction was turned off at a different chord location, symbols were plotted for the calculated incompressible TS logarithmic amplification ratio that corresponded with the measured transition zone. The open symbols indicate the n-factor calculation that corresponded to the chord location of the last fully laminar thin-film gage, while the closed symbols indicate the calculation that corresponded to the first fully turbulent gage. The transition zone shown on the figure helps illustrate the correlated n-factors for the extent of suction used. For this model at test conditions M_∞ = .82 and R_C = 10 million, the TS transition n-factors for cases with suction past 30% chord are slightly lower than those found with little or no suction. The cases with the extent of suction less than 30% chord have incompressible TS amplification ratios at transition of n = 10. The cases with suction past 30% chord have correlated n-factors closer to n = 7. Perhaps this indicates that the transition process on swept LFC/HLFC airfoils becomes increasingly non-linear as the extent of desired laminarization increases.

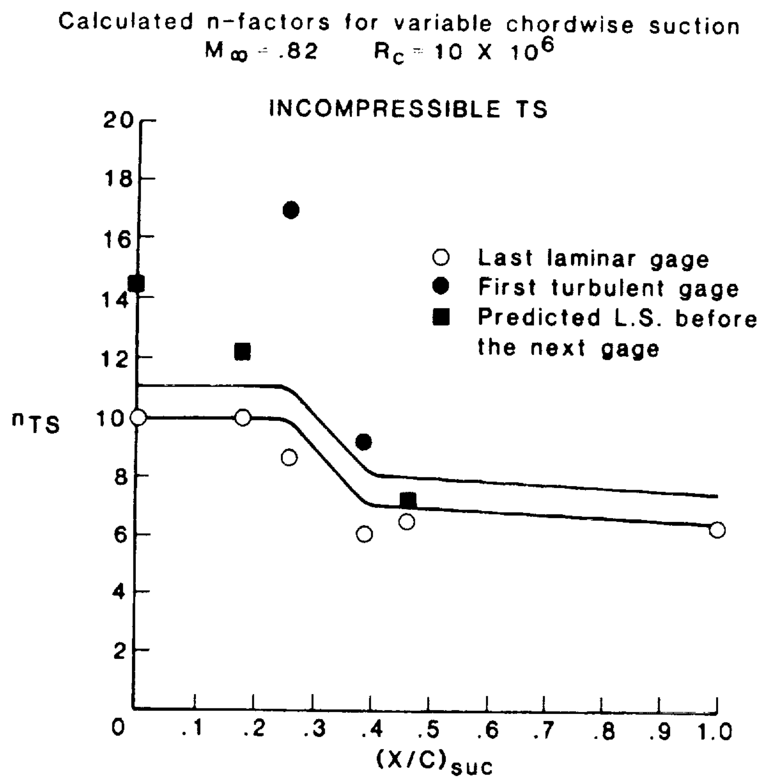

Figure 11

TRANSONIC RESULTS

Figure 12 indicates the results of the incompressible stability analysis of the HLFC data that has a weak shock formed on the rear of the upper surface (R_C = 20 million). As is shown in figure 11 the range of TS amplification at transition is plotted against the extent of suction applied to the airfoil. For the cases ranging from no suction to suction over the first 30% chord, the same trend of correlated n-factors of n = 10 was found. Suction beyond 30% chord, however, shows that transition is increasingly being dominated by non-linear processes as the extent of suction approaches the shock location. These results demonstrate that for a wind tunnel environment, transition can be very sensitive to the formation of a shock.

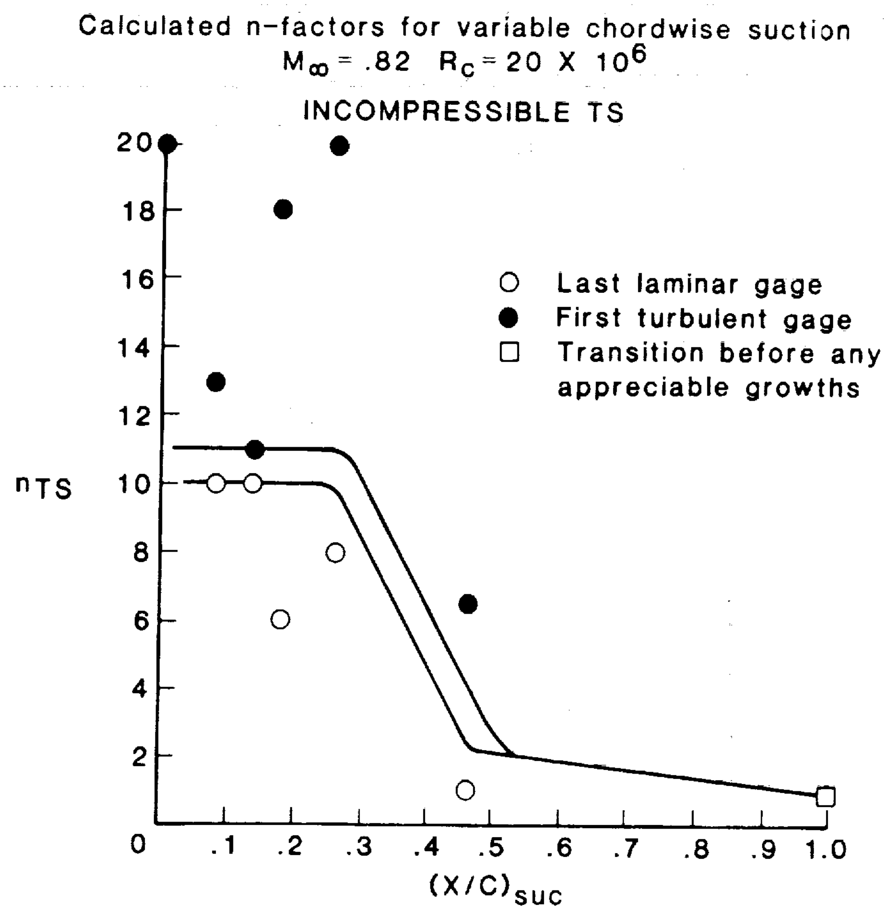

Figure 12

CONCLUSIONS OF TRANSONIC ANALYSIS

The conclusions that were drawn from the incompressible analysis of the transonic data are listed in figure 13. For cases in which full-chord suction distributions were used, transition was sensitive to the rearward attachment point of the sonic bubble. If shockless flow was attained ($R_c < 12$ million) then transition could be maintained very close to the trailing edge. However, if a weak shock appeared ($R_c \geq 12$ million) then transition occurred ahead of the shock for a wide range of over-all suction levels which could not be explained with a linear stability theory. Turning off suction ahead of shock, which simulated an HLFC concept, allowed transition to occur as a consequence of disturbance wave amplification and good theory correlations were found for the available range of R_c. The CF disturbances were generally small and unaffected by suction, while TS disturbances grew rapidly to transition once suction was turned off. The incompressible n-factor correlations at transition for this transonic data were n = 10 when suction was applied up to 30% chord and n = 7 when suction was applied further than 30% chord.

- Full-chord suction cases
  - Transition occurs ahead of shock location for $R_c \geq 12$ million which could not be explained by linear stability theory
  - Transition occurs at trailing edge for shockless flow ($R_c < 12$ million)
- "Hybrid" suction cases
  - Turning off suction ahead of shock allowed natural transition and good theory correlations for range of R_c
  - CF disturbances small and unaffected by suction
  - TS disturbances grew rapidly to transition after suction turned off
- Incompressible correlations at transition
  - 10 near leading edge
  - 7 in the mid-chord region

Figure 13

SAMPLE TRANSONIC CALCULATIONS

Figure 14 shows the results of a compressible TS analysis of the sample transonic case (M_∞ = .82 and R_c = 20 million). For the pressure and suction distribution shown, compressible n-factors were calculated first for a range of frequencies with a wave angle of zero, then for a range of wave angles for the most critical frequency. Since transition was measured between 20 and 28% chord, the compressible TS n-factor at transitions corresponds to n = 5 - 7.5 for the most critical disturbance (f = 7 kHz and ψ = -50°).

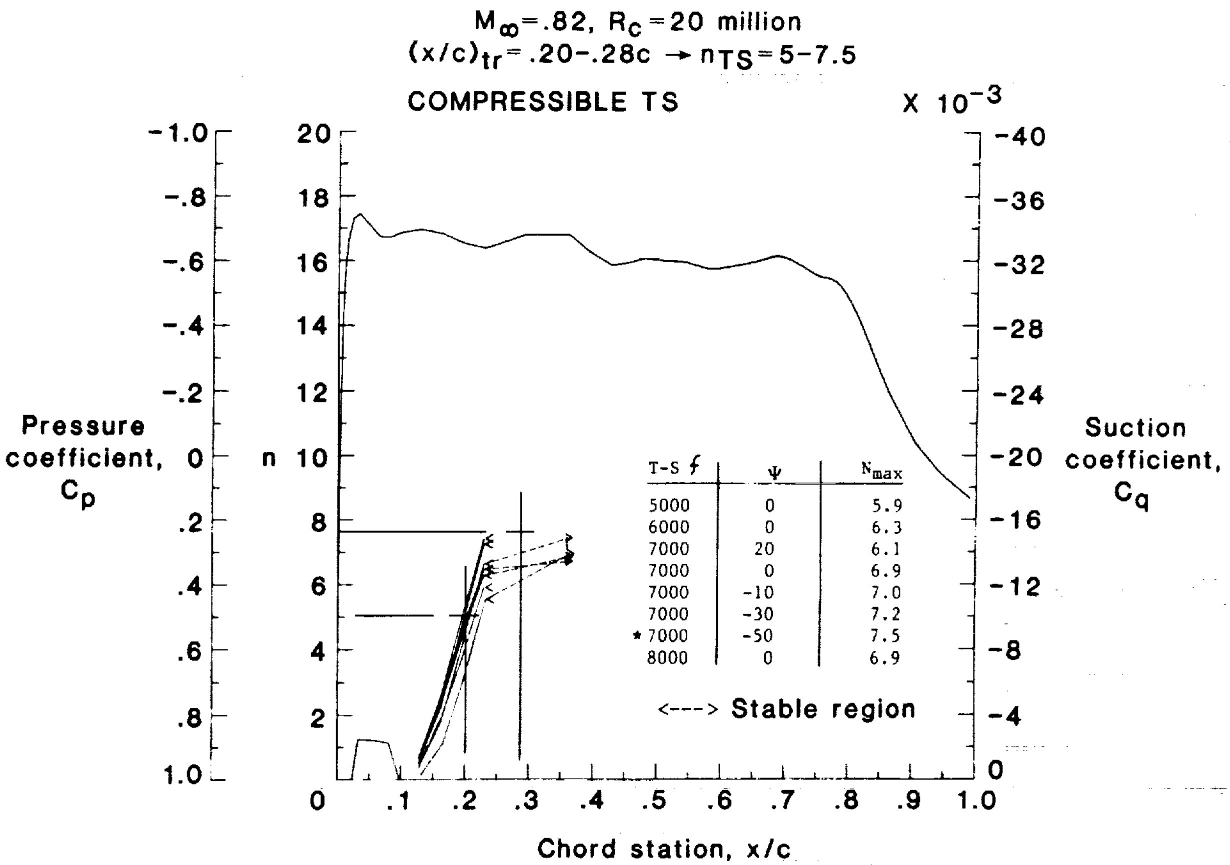

Figure 14

COMPARISONS OF SALLY AND COSAL RESULTS AT TRANSITION

Comparisons of incompressible and compressible stability analysis methods were conducted for a range of M_∞ and the results are tabulated in figure 15. As shown in the figure, compressibility effects reduced the calculated n-factors at transition. The difference accounts for nearly 25% reduction of the calculated amplification for the $M_\infty = 0.4$ to over 50% reduction at $M_\infty = .82$. Both have fairly consistent correlations with the incompressible n-factors of 9 to 10 and the compressible n-factors of 5 to 6. However, as noted earlier, the COSAL analysis involves solutions based on a second unknown (ψ) which increases the time and expense of each compressible case.

M_∞	R_C	n_{TS}-SALLY	n_{TS}-COSAL
.82	20	10.0	4.8
.70	14	10.5	6.3
.40	12	9.0	6.8

- Both have fairly consistent correlation
- COSAL introduces another unknown - ψ
- COSAL is more expensive and time consuming

Figure 15

C-3

SUMMARY

A wide range of low-disturbance wind tunnel data with variations in M_∞, R_c and suction were analyzed based on a linear boundary-layer stability theory. The data, which were from a large chord, swept, supercritical LFC experiment, encompassed both the subsonic and transonic flow regimes. The analysis showed that as far as laminarization through the control of disturbance amplification, the model performed as designed. The CF amplification was successfully controlled through design by using a proper combination of Reynolds number, pressure gradients and sweep angle. The TS amplification could be successfully controlled by suction as long as strong non-linearities (e.g. shocks) were not present on the airfoil. As is shown in figure 16, the TS logarithmic amplification ratios that were calculated at transition were n = 9 to 11 for incompressible theory and n = 4 to 6 for compressible theory. Based on these results, it seems fair to conclude that linear stability theory can be used as a guide in the design of laminar-flow airfoils through transonic speeds. However, a word of caution is needed, increasing conservatism in the choice of a design n-factor is required with increasing lengths of LFC, especially at transonic speeds.

- For the range of subsonic and transonic cases TS disturbances dominated the transition process
- Transition corresponded to
  - Incompressible values of $9 \leq n_{TS} \leq 11$
  - Compressible values of $5 \leq n_{TS} \leq 6$
- Linear stability theory can be used as a guide in the design of laminar flow airfoils at transonic speeds
- Increasing conservatism in choice of n-factor is required with increasing length of LFC

Figure 16

REFERENCES

1. Smith, A. M. O.: Transition, Pressure Gradient and Stability Theory. IX International Congress for Applied Mechanics, Brussels, 1956.

2. Van Ingen, J. L.: A Suggested Semi-Empirical Method for the Calculation of the Boundary Layer Transition Region. University of Technology, Department of Aeronautical Engineering, Report UTH-74, Delft, 1956.

3. Spangler, J. G.; and Wells, C. S., Jr.: Effect of Freestream Disturbances on Boundary-Layer Transition. AIAA Journal, Vol. 6, 1968, pp. 543-545.

4. Kaups, K.; and Cebeci, T.: Compressible Laminar Boundary Layers with Suctions on Swept and Tapered Wings. J. Aircraft, Vol. 14, No. 7, July 1977, pp. 661-667.

5. Srokowski, A. J.; and Orzag, S. A.: Mass Flow Requirements for LFC Wing Design. AIAA Paper 77-1222, August 1977.

6. Malik, Mujeeb R.: COSAL - A Black-Box Compressible Stability Analysis Code for Transition Prediction in Three-Dimensional Boundary Layers. NASA CR-165925, May 1982.

7. Dagenhart, J. R.: Amplified Crossflow Disturbances in the Laminar Boundary Layer on Swept Wings with Suction. NASA TP-1902, November 1981.

8. Harvey, W. D.; and Pride, J. D.: The NASA Langley Laminar Flow Control Experiment. AIAA Paper 82-0567, March 1982.

9. Berry, S. A.: "Incompressible Boundary Layer Stability Analysis of LFC Experimental Data for Sub-Critical Mach Numbers," NASA CR-3999, July 1986.